EXPERIMENTAL SIMULATION OF THE ENERGY PARAMETERS OF THE "ATLAS" CAPACITOR BANK USING A DISK EXPLOSIVE-MAGNETIC GENERATOR

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Abstract

A joint US/Russian Advanced Liner Technology experiment ALT-1 was conducted to simulate the anticipated performance of the Atlas capacitor bank. A disk-explosive magnetic generator and foil opening switch were used to produce an electrical current waveform that reached a peak value of 32.5 MA and that imploded an aluminum liner to an inner surface velocity of 12 km/s.

I. INTRODUCTION

The High Energy Density Hydrodynamics Program at Los Alamos National Laboratory (LANL) has constructed the Atlas capacitor bank to drive the magnetic implosion of cylindrical condensed metal liners in order to obtain high-temperature and high-pressure experimental environments. The Institute of Experimental Physics (VNIIEF) has developed notable pulsed power systems based on a multi-element disk explosive-magnetic generator (DEMG) of 40 cm diameter with electrically exploded copper foil current opening switch (FOS). Liner experiments with such a device have been conducted at a maximum current up to 35 MA [1], however, the liner current rise time τ_1 was half of that required for liner experiments modeling the ATLAS facility. Therefore, VNIIEF developed a new experimental device, providing the current maximum within the range of 25 MA to 35 MA at the current rise time in the interval τ_1 from 3.5 μs to 4.5 μs in a liner load representative of ATLAS facility. This paper reports on the results of the first experiment realized with such a device (ALT-1) on 03 November 1999.

II. EXPERIMENTAL ASSEMBLY AND DIAGNOSTICS

The experimental assembly schematic is shown in Figure 1. The photo of the assembly prior to connection of recording and trigger cables is shown in Figure 2.

The assembly consisted of helical explosive magnetic generator (HEMG), a 10-element DEMG with each module having a diameter of 40 cm (only 5 elements are shown), a unit for DEMG disconnection from the HEMG (DU), an electrically exploded foil opening switch, a high-voltage axisymmetric transmission line (TL) from FOS to the liner load, providing symmetric distribution of the current, and the liner ponderomotive unit (PU) that was connected to the FOS by means of an explosive closing switch (EOS) at the given time moment t_{01} (before the foil explosion in FOS).

A similar explosive magnetic pulsed power system (with a 15-element DEMG) was used to study a plasma liner in the first joint VNIIEF/LANL experiment [2]. The assembly components and operation are described in detail in [1, 2].

Figure 1 also presents the layout of inductive (B-dot) probes in the assembly with the indication of the probe designations in each array. The probes were spaced at 60° over the azimuth. The inductive probes were used to measure the time dependence of the current derivative in the HEMG (HEMG B-dot probes #1-6, positioned at the radius $R_{B\text{-}dot}$=39.2 cm), in the DEMG (DEMG B-dot #1-6, $R_{B\text{-}dot}$=21.505 cm), at the beginning of the coaxial TL above FOS (TL B-dot #1-1 through 1-6, $R_{B\text{-}dot}$ =22.1 cm), at the input to radial TL (TL B-dot #2-1 through 2-6, $R_{B\text{-}dot}$=20.6 cm), above the liner (TL B-dot #3-1through 3-6, $R_{B\text{-}dot}$=4.2 cm). The location of probes in the TL allowed the recording of breakdown phenomena in case any occurred in the shot. The inductive probes (PU B-dot #1--6, $R_{B\text{-}dot}$ = 25 mm, 15 mm and 13.5 mm) were as well placed on the side wall under the liner to measure possible magnetic field penetration under the liner. The location of B-dot probes over the assembly azimuthal angle (view from the load side) is given in Figure 3.

At the radial TL input, the current was also recorded by two Faraday probes (FR1 and FR2, LANL measurements).

The PU design is presented in Figure 4. For the radiographic diagnostics of the liner in the ALT-1 experiment, the PU had a quite long coaxial TL above

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14. ABSTRACT

A joint US/Russian Advanced Liner Technology experiment ALT-1 was conducted to simulate the anticipated performance of the Atlas capacitor bank. A disk-explosive magnetic generator and foil opening switch were used to produce an electrical current waveform that reached a peak value of 32.5 MA and that imploded an aluminum liner to an inner surface velocity of 12 km/s.

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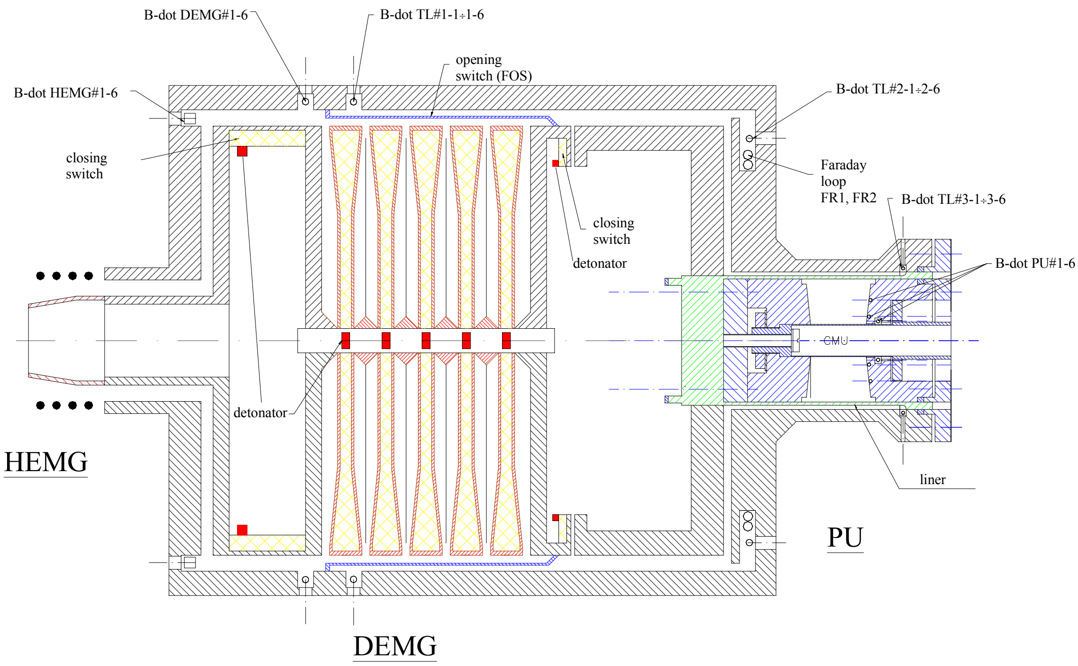

Figure 1. ALT-1 experimental assembly scheme.

Figure 2. ALT-1 assembly photo.

the liner with the conductors, made of AMg-6 type aluminum. The original dimensions of the liner, made of technically pure AD0 type aluminum, were: outer radius - 40 mm, operation height - ~40 mm, thickness - 2 mm. Annealed rings made of soft aluminum (Al995) were used to provide good current contact of the liner with the external and internal conductors of TL. To perform the measurements of the liner dynamic parameters (LANL measurements), a central measurement unit (CMU) with an outer radius R_{CMU} =10 mm was installed along the ponderomotive unit axis under the liner. The velocity of the right liner section in the process of its compression by the magnetic field was measured by a VISAR system. The longitudinal and azimuthal symmetry of the left liner section at R_{CMU} was recorded by the impact optical pins (for protection against the background the tips of the fiber optic pins were covered with a layer of aluminum foil 25 μm thick).

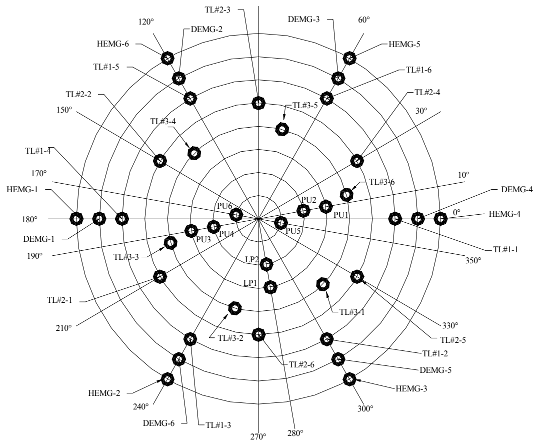

Figure 3. Inductive probes and optical pins azimuthal layout.

Before the experiment, the space under the liner was pumped out through a vacuum chamber to a residual pressure of ~10^{-2} mm of mercury column. Vacuum-tight ports were made on the chamber walls to connect the recording cable lines and to inject the laser beam of VISAR system. The optical pins layout and the location of the VISAR system diagnostic window on the CMU surface are shown in Figure 5.

Two expendable pulsed X-ray sources (U=450 kV, pulse duration at the full width τ_γ =3.5 ns, focal point

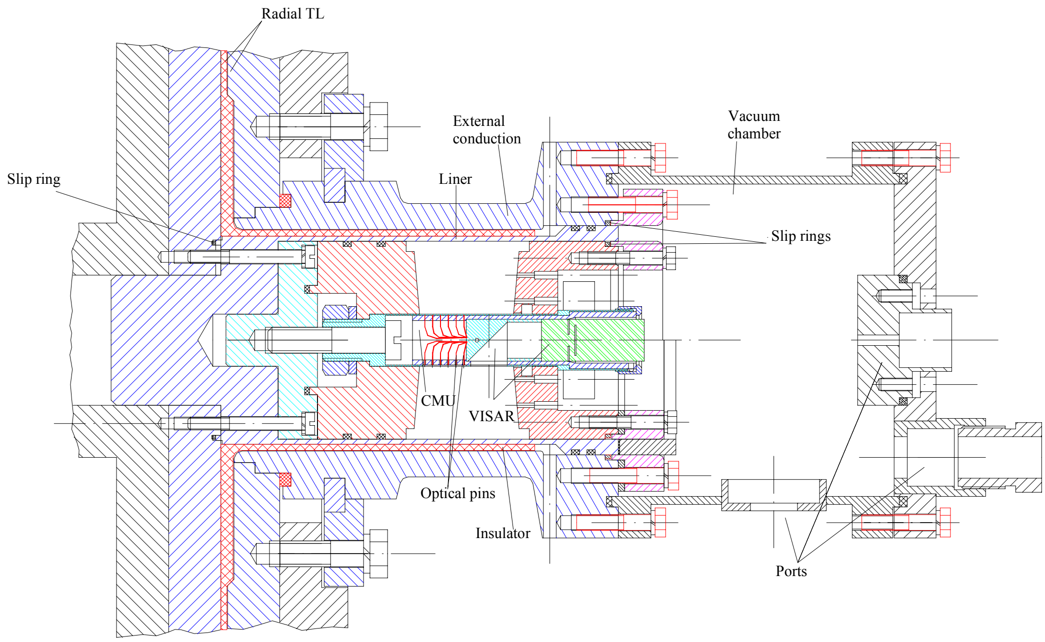

Figure 4. PU design scheme.

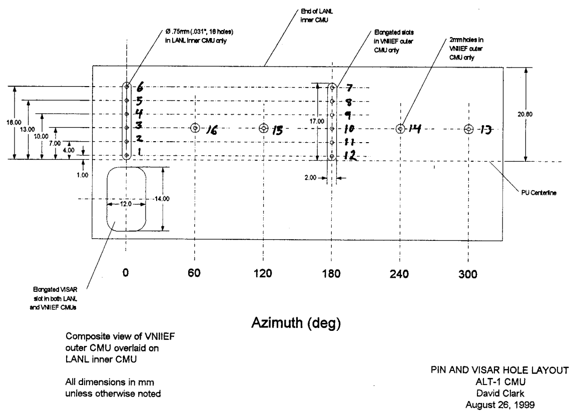

Figure 5. Optical pins layout. Probes 13-16 data were not record.

diameter 3 mm, exposure dose 1 milliroentgen at the distance of 1 m) were used in the experiment to perform a two-frame radiography of the liner at the moment of its approach to the CMU radius (VNIIEF measurements).

III. PRESHOT COMPUTATIONAL-THEORETICAL STUDY

The computation technique was developed previously at VNIIEF [3, 4] and experiments were conducted with the similar pulsed power systems, using a PU with high-velocity exploding liners [1, 2] at the complete current rise time in the load $\tau_l \approx 2$ µs. In those experiments, the copper FOS had a foil thickness of D_f=155 µm.

The best of those experiments [1] was simulated in the nominal calculation by the DISK_FL code [4], a code that became obsolete as a result of the upgrading of the VNIIEF computer complex. A new numerical code UP and MHD, developed by us as a part of a set of UP codes [5], was tested on the same experiment, in which the magnetic flux losses in FOS-PU circuit were described by an effective ohmic resistance $\Omega_{kl} \approx 1.6$ mΩ. The main distinctive features of the new computation technique for DEMG+FOS+PU systems, as compared with the old technique, are:

- the use of the time dependency of the inductance $L_1(t)$ and the minimal radius $R_k(t)$ of one DEMG magnetic flux compression cavity; the dependencies were previously obtained (aside from the UP and MHD code) from a two-dimensional hydrodynamic calculation of the cavity compression by detonation of the explosives disk charges;
- the simultaneous solution of an arbitrary number of 1-D MHD-problems, related by the boundary conditions, that extends the capabilities of UP and MHD code in modeling various pulsed power systems and their loads. Each of these problems may compute not only the magnetic field diffusion and hydrodynamics, but also elasticity-plasticity, electron and ion thermal conduction, radiation transfer, thermonuclear reactions and other processes.

The increase in the time τ_l to ~4 µs that is necessary for ATLAS facility modeling, in the ALT-1 shot required a new mode of FOS operation, characterized, in particular, by a longer duration (~5μs) of FOS foil high effective resistance, as compared with the previous modes (1-2 μs). In previous cases, almost everything was characterizd by a ~1μs long high voltage peak on the FOS. For ALT-1, this part is given to a less high first voltage peak and subsequent smaller peaks, which arise due to radial compression waves in the FOS layers (these waves are generated by a ~30 kbar "electroexplosive" peak of pressure). This may manifest itself on the experimental curves dI(t)/dt. Based on the calculations by the UP and MHD code, the basic parameters of the physical scheme for the ALT-1 shot assembly were chosen. In particular, the foil parameters were D_f=120 μm and L_f=72 cm. The selected mode of FOS operation is characterized by an early start of magnetic flux transfer from DEMG to PU. This considerably constrains the DEMG current rise. According to the calculations, the maximum current in DEMG in ALT-1 shot is almost 2 times lower than the DEMG current in the earlier experiments [1,2] and is not much higher than the load current amplitude.

The pre-shot calculations included the selected values and the possible errors in the basic parameters of experimental assembly:

- load initial inductance L_0=7.5 nH;
- desirable operation range of DEMG initial current I_0=(6.0-6.6) MA and its possible jitter, that can not be excluded *a priori,* I_0=(5.5÷7.0) MA;
- possible time value for connection of the PU to FOS t_{0l}=(23.5±0.5) μs from the moment of By-19-2 firing unit actuation (DEMG, DU, ECS detonators are triggered by this unit, see Figure 1);
- effective ohmic resistance of FOS-PU circuit Ω_{kl}≈(1.6±1) mΩ.

For the above-mentioned intervals of expected and possible magnitudes of DEMG initial current, the unfavorable combination of the errors mentioned above led to a spread in the predicted current maximums in the PU, (27-36) MA and (26-36) MA, and to a spread in predicted times of liner impact on the target (CMU) t_f, (31÷34) μs and (30÷34) μs. Such a large pre-shot spread in the predicted PU currents and in liner (R-t) – diagrams is characteristic of the first ALT-1 experiment only, which for the first time tested a new mode of FOS foil operation, the aluminum PU and other design innovations, and also a new computational technique for the systems of (DEMG+FOS+PU) type. For the given values of t_{01} and Ω_{kl}, the calculations predicted the "self-adjustment" of the current maximum in PU and, respectively, a small spread in the predicted liner (R-t)-diagrams and the times of liner – CMU impact t_f. For example, at t_{0l} =24 μs and Ω_{kl} =1.6 mΩ, the predicted spread is Δt_f=0.4 μs. For the most likely DEMG initial current, I_0=(6.0÷6.6) MA, and for the above-described *a priori* possible spread in the assembly parameters, the time interval for the expected liner impact on CMU was t_f = (29.9-32.9) μs at the maximum liner velocity u_{max}=(7.5-14) km/s.

Pre-shot studies also included a 2-D MHD-calculation of the liner PU [6]. That calculation showed that the liner-wall interaction affected the one-dimensional character of liner – CMU impact only in the immediate vicinity of the PU end face elements. No account was taken in the calculation of the growth of small perturbations in the melted zone of the liner close to its outer surface. Such growth should actually take place by the time of the impact. The melted zone represents 60% of the liner mass.

IV. THE MAIN RESULTS OF THE ALT-1 EXPERIMENT AND COMPARISON WITH THE PRE-SHOT CALCULATIONS

Four signals from the HEMG B-dot probes were recorded in ALT-1 experiment. One of them was distorted by electromagnetic noise and was ignored in post-shot analysis. The maximum value of the average current derivative was 0.21 MA/μs, the maximum current in HEMG at the beginning of the DEMG operation was 5.9 MA, i.e. the initial DEMG current turned out to be close to the lower value of the expected range (6.0-6.6) MA.

All six signals from the DEMG B-dot probes were recorded. The corresponding current derivative pulses and the averaged pulse are in Figure 6.

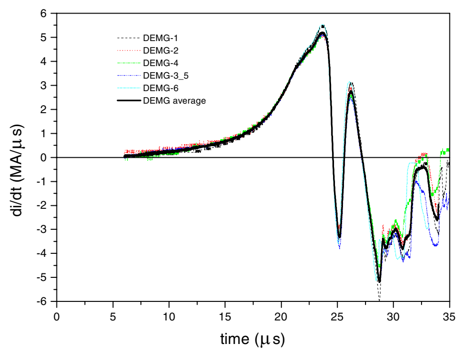

Figure 6. DEMG current derivative and average derivative.

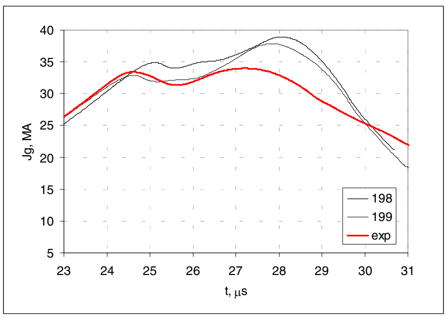

Figure 7. DEMG current. Comparison with preshot calculations.

The dependence of the averaged value of current in the DEMG is shown in Figure 7.

The DEMG current curve has two peaks: I_{1max}(t=24.6 μs) = 33.4 MA and I_{2max}(t=27.2 μs) = 34 MA. The current drop after I_{1max} is connected with the magnetic flux transfer from the DEMG to the load after the FOS foil electrical explosion. Further current rise to I_{2max} is due to flux compression in DEMG-PU circuit under the effect of continuing operation of DEMG modules. Figure 7 also shows the calculated pre-shot current curves obtained at I_0=6.6 MA (calculation 199), I_0=6.0 MA (calculation 198), t_{0l} =24 μs and Ω_{kl} =1.6 mΩ.

Figure 8 shows the current derivative pulses from B-dot probes TL #1-1 through 1-6. The variation in the shape of the pulses is connected with a non-symmetry of the process of foil electrical explosion across the azimuthal angle. The pulse amplitude is underrated because of the radial compression of the dielectric frames (the probes coils are wound on them) by pressure, occurring in the TL as a result of the foil electrical explosion and the pressure of magnetic field under the foil. In the calculations, the pressure pulse amplitude was ~30 kbar. The pressure pulse shape may have azimuthal asymmetry that may affect the shape of signals from B-dot probes, installed at different azimuthal angles.

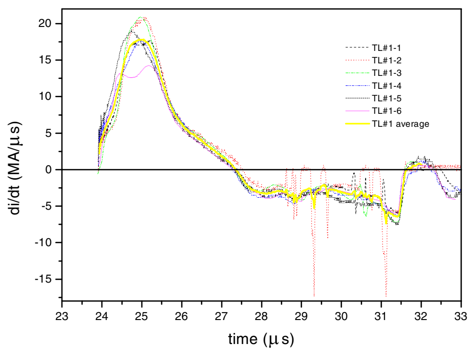

Figure 8. Current derivative vs time, and averaged curve based on measurements above FOS.

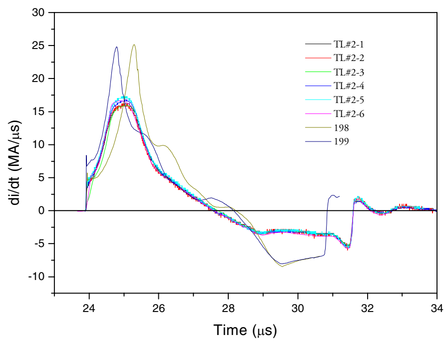

Figure 9. Current derivative at the radial TL inlet in comparison with preshot calculations.

Figure 9 shows the pulses from B-dot probes TL #2-1through 2-6. Good agreement of the signals shape can be seen, as well as a rather close agreement in their amplitudes (17.9÷19.5) MA/μs. The time of PU connection to FOS was $t_{0l(exp)}$=23.9±0.1 μs. So, the observed moment $t_{0l(exp)}$ was within the predicted interval t_{0l}=(23.5±0.5) μs. Figure 9 also presents the calculated pre-shot curves of current derivative, which are much different from the experimental curves. The calculated maximum of current derivative was ~1.3 times higher than the experimental one, and the characteristic duration was ~1.3 less in calculations, than in the experiment. This can be explained by a corresponding angle asymmetry of FOS operation, that can be proved by the data from B-dot probes TL #1-1 through 1-6.

The maximum value of current at the inlet to the radial TL is within the range (30.4÷33.6) MA. The average magnitude of maximum current was I_{max}(t=27.6 μs)=(31.5±1.5) MA (as the B-dot probes measurements accuracy was ≥5%). Complete time of current rise τ_I is 3.7 μs. Figure 10 gives the time dependent plots for the current at the radial TL inlet, that were the result of the processing of the signals from Faraday probes FR1 and FR2.

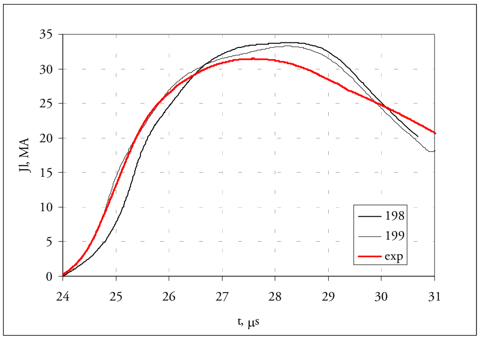

Figure 10. Current at the radial TL inlet. Comparison with calculations.

The maximum current magnitude was 32.5 MA (measurements accuracy ~1%). Figure 10 also presents the curves from the above-mentioned pre-shot calculations.

The analysis of signals from the B-dot probes TL #3-1 through 3-6 showed that all of the current measured precisely at the radial TL inlet was also flowing in PU, indicating the absence of TL breakdowns. It should be mentioned that this was the first experiment in which such a long lifetime of the insulator of TL between FOS and PU was observed. In accordance with the B-dot probes TL #1-1 through 1-6 (see Figure 8), the trailing edge of the derivatives reflected the processes in PU even after the shock waves, generated by HE detonation in disk elements, release into TL.

Only two signals ($R_{B\text{-}dot}$ =15 mm) out of six signals from B-dot probes PU #1-4 were successfully recorded. The magnetic field did not penetrate under the liner until t=30 μs. The initiation of signals from these probes at t>30 μs is connected with the liner passing the radius $R_{B\text{-}dot}$=15 mm (i.e. with magnetic field above the liner).

The radiographic film did not survive in the experiment. The film cassettes had shrapnel damage from aluminum fragments of the TL return conductor above the liner. These fragments expanded with a rate of 2 km/s under the effect of magnetic field pressure in the radial direction, opposite to the liner implosion direction.

Despite the fact that this was the first attempt to use VISAR system for liner velocity measurements in a DEMG experiment, and despite the fact that the experiment was performed in extremely unfavorable weather conditions, the obtained VISAR data were of rather a good quality. Figure 11 shows the time-dependency of the liner velocity, obtained as the result of VISAR data processing.

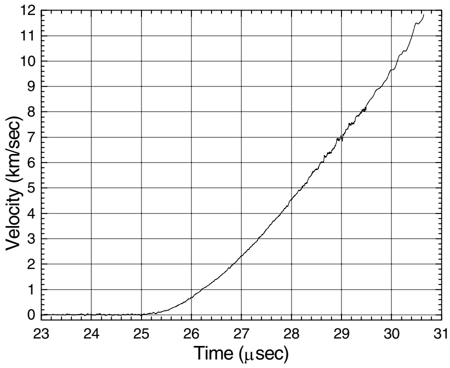

Figure 11. Liner velocity vs time according to VISAR.

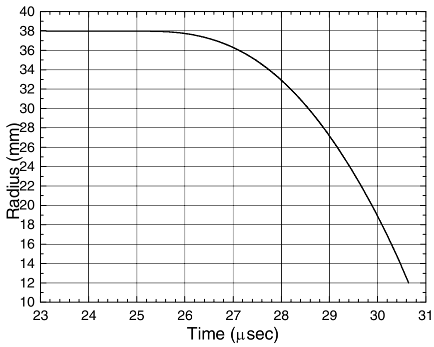

Figure 12. Liner R-t diagram according to VISAR.

Figure 12 presents the R-t diagram of liner motion. The VISAR data permitted the plotting of these dependences for the time interval from 23.0 μs to 30.65 μs. The experimental data are in good agreement with the calculations, as shown in Figure 13.

A three-fold radius compression of the liner is achieved at R_l=12 mm. The liner velocity at this time is u_l~11.6 km/s. At t=30.6 μs, the radius R_l=12 mm, and the velocity is u_l≈11.8 km/s. The radius and velocity extrapolation of data shows that the liner approaches R_{CMU} =10 mm at t=30.8 μs with a velocity u_l>12 km/s.

Because of some technical difficulties, the information from the optical pins # 13-16 was not recorded (see Figure 5). Figure 14 gives the time of the beginning of the probes signals (defined by the moments of sharp increase of signals).

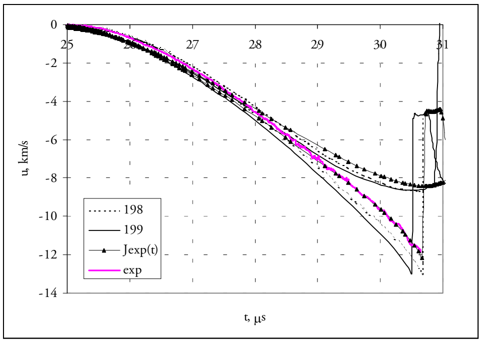

Figure 13. Experimental and computed liner inner boundary velocity vs time.

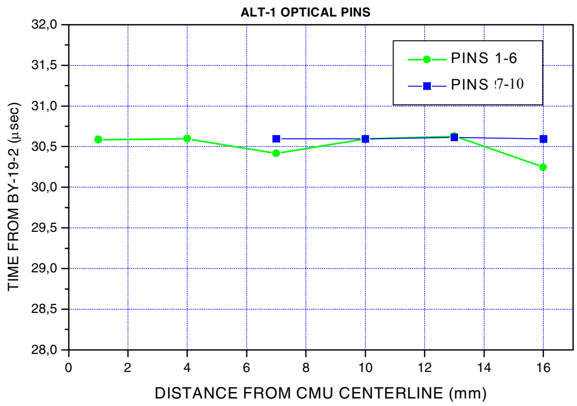

Figure 14. Moments of initiation of signals from the optical pins (radius is 9.5 mm). There were two lines of probes in 180°. Data from probes 11 and 12 were unlikely early (probably because of their background shield damage). Probes 1-6 are counted from left to right, probes 7-12 are from right to left.

The agreement between the onset of the signals for probes #1-6 and the onset of probes #7-10 (see Figure 5) indicates a good azimuthal symmetry of the liner impact on the CMU. A rather good one-dimensional character of liner motion was also observed, in agreement with the pre-shot predictions (see Figure 6). The early onset of the probe # 6 signal might be explained by a manifestation of the 2-D side effects.

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